ASSESSMENT OF MODELED RECEIVED SOUND PRESSURE LEVELS AND MOVEMENTS OF SATELLITE-TAGGED ODONTOCETES EXPOSED TO MID-FREQUENCY ACTIVE SONAR AT THE PACIFIC MISSILE RANGE FACILITY: FEBRUARY 2011 THROUGH FEBRUARY 2013

FINAL REPORT

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ABSTRACT

The Pacific Missile Range Facility (PMRF) off the island of Kaua'i is the site of regular United States (U.S.) Navy training, some of which involves mid-frequency active sonar (MFAS) use from different types of military sound sources. PMRF includes acoustic instrumentation which allows for passive acoustic monitoring (PAM) capabilities to detect and localize sounds such as vocalizing marine mammals. Recent boat-based studies at PMRF have utilized real-time PAM (in conjunction with the Marine Mammal Monitoring on Navy Ranges project) to detect odontocetes for vectoring a field tagging boat to groups in order to increase the likelihood of deploying satellite tags. The resulting data have allowed for an assessment of habitat use and range of several different species. Some of these boat-based tagging efforts were timed to occur just before Submarine Commanders Courses (SCCs) occurring on PMRF so that animal movements and diving behavior could be measured both before and during sonar use. PMRF PAM data and tag data were used in this initial analysis to estimate exposure levels for tagged animals and determine whether any large-scale movements of these animals may have occurred in response to MFAS exposure. We first assessed temporal and spatial overlap between the location data from satellite tags and available acoustic recordings and selected a subset of data for which there was sufficient overlap. The MFAS transmission times (determined directly using sounds received on the range hydrophones), ship positions at time of transmissions (provided by PMRF) and animal locations (determined from satellite tag positions) allowed estimation of the sound pressure levels the tagged animals were exposed to using the U.S. Navy's Personal Computer Interactive Multi-sensor Analysis Tool propagation model. Between February 2011 and February 2013, satellite-tag data were obtained from 23 individuals of four species of odontocetes: rough-toothed dolphins (*Steno bredanensis*, *n* = 8), common bottlenose dolphins (*Tursiops truncatus*, *n* = 6), false killer whales (*Pseudorca crassidens*, *n* = 3) and short-finned pilot whales (*Globicephala macrorhynchus*, *n* = 6). Satellite tags were deployed on five different occasions during this period, with four of the five efforts timed to coincide with SCCs (February 2011, August 2011, February 2012, February 2013). The remaining field effort occurred prior to the July 2012 Rim of the Pacific exercise. Initial analysis of tag and PMRF data revealed temporal and general spatial overlap for eight individuals of three species: bottlenose dolphin, short-finned pilot whale, and rough-toothed dolphin. This initial exposure analysis was restricted to one bottlenose dolphin, one short-finned pilot whale, and two rough-toothed dolphins. Based on photo-identification and association analyses, all tagged individuals are known to be from populations generally resident to the islands of Kaua'i and Ni'ihau. Satellite-tagged animals were exposed to estimated received levels of: 130 to 144 decibels for two rough-toothed dolphins, referenced to a pressure of 1 micropascal (dB re: 1μPa) root mean square, hereafter dB; 149 to 168 dB for a bottlenose dolphin; and 141 to 162 dB for a short-finned pilot whale. The bottlenose dolphin showed no large-scale movements out of the area during sonar exposures despite these relatively high predicted received levels, and the short-finned pilot whale actually moved towards areas of higher exposures during the third day of a 3-day period of regular MFAS use. There are a number of acknowledged limitations in terms of the modeling assumptions and the level of resolution on individual response relative to specific sonar transmissions. However, these results demonstrate that this novel integrated approach of using location data from satellite-tagged individuals and modeling to estimate received levels from acoustic recordings from the PMRF hydrophones is a viable and promising approach to examine both estimated exposure levels and potential large-scale movement reactions of tagged individuals.

INTRODUCTION

The Pacific Missile Range Facility (PMRF) off the island of Kaua‘i is the site of regular United States (U.S.) Navy testing and training, some of which involves the use of mid-frequency active sonar (MFAS) systems. PMRF is instrumented with 219 bottom-mounted hydrophones that allow for passive acoustic monitoring (PAM) capabilities in real-time and/or with recorded acoustic data, to detect and localize vocalizing marine mammals or other sources of sound (e.g., Tiemann et al. 2006; Martin et al. 2013; Baird et al. 2013a). Multi-species boat-based studies of odontocetes off Kaua‘i and Ni‘ihau have been undertaken since 2003 (Baird et al. 2013b). In recent years, boat-based studies involving deployment of Low-Impact Minimally Percutaneous External-electronics Transmitter (LIMPET) satellite tags on odontocete cetaceans on and around PMRF, combined with real-time PAM (in conjunction with the Marine Mammal Monitoring on Navy Ranges project) to increase boat-based encounter rates, have allowed for assessments of habitat use and range of several different odontocete species (Baird et al. 2013a, 2013c). Information obtained from these studies have provided evidence for resident, island-associated populations of rough-toothed dolphins (*Steno bredanensis*), common bottlenose dolphins (*Tursiops truncatus*) and short-finned pilot whales (*Globicephala macrorhynchus*) off Kaua‘i and Ni‘ihau, with each species varying in movement patterns and habitat use (Baird et al. 2008, 2009, 2013a, 2013c; Martien et al. 2011).

Some of these boat-based efforts were timed to occur in association with Submarine Commanders Courses (SCCs) occurring on PMRF, and acoustic data were also recorded from a number of PMRF hydrophones. We compared location data from satellite tags deployed on odontocetes with information on vessel positions and MFAS transmissions using data from PMRF. The purpose was to identify baseline behavioral movement patterns in tagged cetaceans as well as potential large-scale movements in response to MFAS transmissions. We first determined if there was overlap of tag data and available PMRF recorded acoustic data. The recorded data is required to determine if MFAS was utilized and if so, the precise times of transmissions. In cases when sonar use was concurrent with location data derived from satellite tags, we then estimated the received sound pressure levels of MFAS at the locations of tagged animals. As well as allowing for an assessment of MFAS exposure levels of tagged animals, this information can be used to assess whether there were large-scale movements of animals that may have occurred in response to received sounds, as has been demonstrated for Blainville’s beaked whales (*Mesoplodon densirostris*) (Tyack et al. 2011). We also used information from photo-identification of tagged and companion individuals to help interpret results, given the evidence for resident, island-associated populations.

METHODS

Satellite Tag Data

Boat-based field efforts were undertaken on five different occasions off Kaua‘i between February 2011 and February 2013[1] (see Table 1). Details on field methods are available in Baird et al. (2013a, 2013c). Four of the five efforts were timed to coincide with SCC training events, with the first effort starting at the end of the February 2011 SCC, and efforts starting before the August 2011, February 2012, and February 2013 SCCs. The remaining field effort occurred prior

[1] An additional effort was undertaken prior to the August 2013 SCC.

to the July 2012 Rim of the Pacific (RIMPAC) exercise. Tags used were either location-only (Wildlife Computers Smart Position or Temperature Transmitting Tag [SPOT]5) or location-dive (Wildlife Computers Mk10A) tags in the LIMPET configuration, attached with two titanium darts with backward facing petals. Tags were remotely deployed with a DAN-INJECT JM Special 25 pneumatic projector from a small boat. Tags were programmed to transmit from 8 to 18 hours (hr) per day depending on species and tag type, with Mk10A tags transmitting for longer periods to maximize the likelihood of obtaining dive data. Prior to each field effort, satellite-pass predictions were carried out using available Argos schedules to determine optimal periods for transmission, given satellite overpasses for the ~60-day period from the start of tag deployments. Location-dive tags were set to record a time series (recording the depth once every 2.5 minutes [min] for short-finned pilot whales), as well as dive statistics (e.g., start and end time, maximum depth, duration) for any dives ≥ 20 meters (m) in depth, with depth readings of 3 m being used to determine the start and end of dives, thus dive durations are slightly negatively biased. Given typical odontocete descent and ascent rates of 1 to 2 meters per second (m/s), dive durations recorded are likely only 3 to 6 seconds shorter than actual dive durations.

Satellite tags were remotely deployed on three of the four odontocetes species most frequently encountered off Kaua‘i (Baird et al. 2013b): rough-toothed dolphin, common bottlenose dolphin (hereafter bottlenose dolphin), and short-finned pilot whale, as well as one rare species (false killer whale, *Pseudorca crassidens*). Each tagged individual was assigned a unique identifier including a two-digit species code (e.g., Gm = *Globicephala macrorhynchus*), and a number reflecting the number of tags deployed on that species in the Cascadia Research Collective database (e.g., GmTag070 is the 70th short-finned pilot whale tagged by Cascadia Research Collective). The remaining frequently encountered species, spinner dolphin (*Stenella longirostris*), is not suitable for tagging using the current technology available for remotely deployed LIMPET tags, due to the small size of this dolphin and the thickness of its dorsal fin.

Locations of tagged individuals were estimated using the Argos Data Collection and Location System with a least-squares method and assessed for plausibility using the Douglas Argos-Filter version 8.2 (Douglas et al. 2012) to remove unrealistic locations; this approach follows protocols applied previously (Schorr et al. 2009; Baird et al. 2010, 2011a, 2013c). This filter includes four user-defined variables:

1) Maximum redundant distance—consecutive points separated by less than a defined distance are kept by the filter because Argos location errors rarely occur in the same place, thus nearby temporally consecutive points are assumed to be self confirming;
2) Standardized location classes (LCs, defined below) that are automatically retained;
3) Maximum sustainable rate of movement; and
4) Rate coefficient (Ratecoef) for assessing the angle created by three consecutive points; the rate coefficient algorithm takes into account that the farther an animal moves between locations, the less likely it is to return to or near to the original location without any intervening positions, creating an acute angle characteristic of typical Argos error.

We automatically retained locations separated from the next location by less than a maximum redundant distance of 3 kilometers (km), as well as LC2 and LC3 locations

(i.e., estimated error of <500 and <250 m, respectively; Argos User's Manual). LC1 locations (i.e., with estimated error between 500 and 1,500 m), as well as LC0, LCA, LCB, and LCZ locations (i.e., with no estimation of accuracy), were only retained if they passed the Douglas Argos-Filter process. For maximum sustainable rate of movement, we used 20 km h^{-1} for bottlenose dolphins and rough-toothed dolphins, and 15 km h^{-1} for short-finned pilot whales, based on maximum travel speeds noted during observations of fast-traveling individuals in Hawai'i (R.W. Baird, pers. obs.). We used the default Ratecoef for marine mammals (Ratecoef = 25).

Resulting filtered location data were processed with ArcGIS to determine water depth and distance from shore. When more than one tag was deployed on the same species, we assessed whether the behaviors of tagged individuals were coordinated with one another during the period of overlap by measuring the straight-line distance (i.e., not taking into account potentially intervening land masses) between pairs of individuals when locations were obtained during a single satellite overpass (~10 min). We used both the average distances between pairs of individuals and the maximum distance between pairs to assess whether individuals were acting independently, following protocols described by Schorr et al. (2009) and Baird et al. (2010).

We initially used switching state-space models (Jonsen et al. 2007) to estimate the probability that tagged individuals were in a particular behavioral mode (e.g., transiting or foraging ("area-restricted search")). However, model output for all four tagged individuals considered in acoustic propagation modeling (see *Results*) indicated that individuals remained in a single behavioral mode during the entire periods of tag data collection. In all cases, *b* values (see Jonsen et al. 2007) were >1.5, thus all individuals were considered to be engaged in area-restricted searches during the period of tag data, and the state-space model results are not considered further.

Data obtained from the Argos System were processed through the Wildlife Computers DAP Processor version 3.0 to obtain diving and surfacing data from the location-dive tags. To visualize the dive and surfacing data, a pseudotrack was developed, using similar methods to those noted in Baird et al. (2013a).

Acoustic and Ship Track Data

Methods previously described (Martin and Manzano-Roth 2012) for estimating the MFAS exposure levels on marine mammals which are visually sighted also applies to tagged animals. Martin and Manzano-Roth (2012) discuss accuracies involved in the process and required information in order to estimate the sound pressure level marine mammals are exposed to. Information on the MFAS ship track and times of MFAS transmissions are required in conjunction with tag location data in order to estimate the Received Level (RL) which tagged animals were exposed to. The RL is the modeled sound pressure level (SPL) in dB re 1 micropascal at the geographic location of the tagged animal with several species-specific typical depth regimes assumed. Equation 1 provides the simplistic form of the sonar equation where the RL is defined as the Source Level (SL) of the MFAS transmission minus the Transmission Loss (TL) for the sound propagating from the ship to the animal location.

Equation 1: $RL = SL - TL$

The TL is complex and heavily effected by factors such as the bathymetry between the source and animal and environmental factors including sound velocity profiles, wind speed and bottom characteristics. Ship positions were provided as global positioning system position updates in PMRF standard data products. Errors associated with tag locations were discussed in the prior section and accounting for these can provide upper and lower limits of the estimated RLs. The time between a tag update and an MFAS transmission also must be considered, as that impacts potential movement of the tagged animal over this time period. Animal depth, while zero at the time of tag updates, is modeled using species-specific typical depth regimes to allow searching in depth for maximum SPLs. These time differences and tag accuracies are most important for close encounters between the ship and animal (e.g., under 10 km) or when the time difference allows animal movement on the order of multiple km. Otherwise the corrections to the distances between source and animal are relatively small percentages of the total distance and the estimated RLs do not show large differences due to the logarithmic relationship of the sound pressure level with respect to distance from the ship to the animal. Recorded hydrophone acoustic data is utilized to determine precise times of MFAS transmissions as this information is not normally logged. Recordings were made from 31 hydrophones in 2011 and 2012, and 62 hydrophones in 2013, for varying periods associated with each of the five tag deployment periods (Table 1). Determining transmission times was undertaken using automated PAM detection, classification, and localization algorithms for both destroyer AN/SQS-53C and frigate AN/SQS-56 sonars (hereafter, 53C and 56 sonars, respectively), which aid in processing the large volumes of data.

A number of assumptions were necessarily made regarding source levels (SLs) for MFAS sources. Sources were assumed to have no directionality in either azimuth or elevation angles for this initial analysis given security concerns. Specific SL values provided by the U.S. Navy (Evans and England 2001) for two U.S. Navy sonar systems are: destroyers with AN/SQS-53C sonar have a nominal SL of 235 decibels referenced to a pressure of 1 micropascal (dB re: 1μPa)[2] root mean square (RMS) at center frequencies of 2.6 and 3.3 kilohertz, and frigates with the AN/SQS-56 sonar have a nominal SL of 223 dB at center frequencies of 6.8, 7.5, and 8.2 kilohertz. When non-U.S. Navy ships were involved in training events and information was not available on their sonar systems, the sonar type for a similar U.S. Navy ship was utilized (e.g., foreign destroyers as U.S. destroyer sonars and foreign frigates as U.S. frigate sonars).

Transmission loss was estimated using the U.S. Navy's Personal Computer Interactive Multi-sensor Analysis Tool (PCIMAT), based upon the Comprehensive Acoustic System Simulation model. The model uses sound velocity profiles for historical dates/times and locations; detailed bathymetry of the area; and selectable bottom type, wind speed, and sea state to estimate a TL at a location and depth given a source location and operational parameters.

Surface-ducted sound propagation favoring transmission near the sea surface in the PMRF region is quite common, resulting in higher estimated RLs when animals are located in the surface duct (i.e., region of the water column from the surface to ~30-m depth). The RL is tightly coupled to the strength of the surface duct (i.e., strong vs. weak ducting). When considering effects of RLs on animals at PMRF, the ducted propagation needs to be considered

[2] Sound pressure levels are given as broadband RMS levels in dB re: 1μPa RMS, hereafter referred to as dB.

as the RLs are much higher than would be estimated without modeling the ducting. The PCIMAT propagation model fully considers these factors based on sound velocity profiles used, as well as the complex bathymetry for bottom-reflected paths when providing TL estimates. The extent to which these model predictions reflect real propagation depends on the extent to which sound velocity profiles used reflect actual environmental conditions at the time of MFAS use.

Using the acoustic hydrophone data periods of time of MFAS transmissions (from either a 53C or 56 sonar, or in some cases multiple active vessels) were identified. For each location estimate from a tagged individual that has passed the Douglas-Argos Filter, the time difference from the sonar pulse closest in time was determined. For each MFAS pulse closest in time to the determined tagged animal locations, the positions for both the ship and tagged animal were utilized in the PCIMAT model to obtain the distances between ship and animal and the transmission losses for each situation. The ship's MFAS depths are known, however, the depth used for modeling RLs at the tagged animals varied for each species.

Three different approaches were utilized for animal depth to model RLs based on available data on diving behavior of the three species tagged. For rough-toothed dolphins, which spend most of their time in near-surface waters (Baird unpublished), the maximum RLs in the upper 20 m of the water column were determined. For a bottlenose dolphin, which regularly dive deeper than 50 m (Baird unpublished), the maximum and minimum RLs in the upper 50 m of the water column were determined. For short-finned pilot whales, the deepest-diving of the three species, RLs were determined for 10-m depth and for 200-m depth. Dive data were obtained from one Mk10A tag deployed on a short-finned pilot whale during a period where RLs were estimated, however as depth is only recorded in a 2.5 minute time series, it is not possible to say precisely where in the water column the tagged animal was during particular sonar pings. However, we utilized the dive statistics (maximum depths of dives) obtained during the periods when RLs were estimated to help interpret our results given our choice of estimating RLs at 10-m and 200-m depths for this species.

RESULTS

Satellite tag data were available from individual cetaceans tagged during five boat-based field projects undertaken off PMRF between February 2011 and February 2013. During these efforts, data were obtained from 23 tagged individuals of four species: short-finned pilot whales, bottlenose dolphins, rough-toothed dolphins, and false killer whales (Baird et al. 2013a, 2013c; Table 1). While PAM acoustic recordings have been made for all of the SCCs since 2011, overlap with tag data is variable and in some cases limited recorded data is available before the SCCs. This initial comparison of tag and available acoustic data recorded in conjunction with SCC training events revealed temporal and general spatial overlap in the two data sets for eight tagged individuals of three species. Three tags were deployed on two species in February 2012; however, two of the three tags (one pilot whale and one rough-toothed dolphin) had stopped transmitting prior to the start of the February 2012 SCC. The third tagged individual, a short-finned pilot whale, was moving southeast off the northeast side of Kaua'i prior to the start of the SCC, and was to the southeast of Kaua'i during the majority of the SCC. Thus it would have only been possible to calculate RLs for one or two locations at the start of the SCC, due to shadowing of transmissions by the island. Eight tags were deployed on three species (including

three false killer whales[3]) in June/July 2012, prior to the RIMPAC exercise. However PAM recorded data were not obtained in relation to the RIMPAC exercise, and all tags had stopped functioning prior to the recording of any MFAS associated with the August 2012 SCC. Of the remaining 12 tagged individuals, tagged during three different periods, four of the tags stopped transmitting prior to the start of MFAS transmissions. Of the remaining eight individuals, one or two individuals of each of the three species were chosen for further consideration based on the potential exposure of individuals to MFAS and availability of PAM data to assess MFAS use before, during and after SCCs (Table 1). Specific details of which individuals were used for estimating RLs are outlined below for each species.

The four tagged individuals used in this analysis for estimating RLs including one bottlenose dolphin and one short-finned pilot whale, both tagged before the February 2013 SCC, and two rough-toothed dolphins tagged before the August 2011 SCC. During the SCC February 2013 period, two different surface ships produced MFAS, a destroyer operating a 53C sonar and a frigate operating a 56 sonar. The MFAS transmission of these vessels occasionally occurred independently of one another and sometimes was simultaneous, but generally occurred in similar periods (see below). Tags deployed on the bottlenose and rough-toothed dolphins were location-only tags (SPOT5s) set to transmit 17 hours per day, while the tag deployed on the short-finned pilot whale was a location-dive tag (Mk10A, see Table 2) set to transmit 18 hours per day. After filtering Argos data with the Douglas-Argos Filter, approximately one animal location per hour of transmission was retained. Only those locations which were obtained at relatively short intervals from MFAS transmissions were used for estimating RLs.

Bottlenose dolphins

Location data were available for three bottlenose dolphins (one tagged in 2011 and two tagged in 2013, see Table 1) with temporally overlapping MFAS data (Table 1). The individual tagged prior to the August 2011 SCC remained near-shore off the southeast side of Kaua‘i for several days before, during, and after the SCC, thus there was no means of estimating RLs due to shadowing of transmissions by the land mass. For the three individuals tagged in February 2013, one tag stopped transmitting prior to the start of the SCC, one stopped transmitting prior to the end of the SCC, and the third transmitted both during and after the end of the SCC. Given the complete tag data record before, during, and after MFAS transmissions, this individual (TtTag010) was considered for further analyses. Eighteen locations of TtTag010 were available for modeling RLs from the 53C sonar. Nineteen locations of TtTag010 were available for modeling RLs from the 56 sonar, 16 of which were also modeled for the 53C sonar.

For the bottlenose dolphin, both the maximum and minimum RLs were estimated within the upper 50 m of the water column for each location. The lowest maximum modeled RLs in the upper 50 m of the water column for the 53C (i.e., 147 dB) were higher than the highest maximum modeled RL for the 56 sonar (i.e., 136 dB). Thus, only results from the 53C are considered further; although it is possible that the presence of two different sonars could be perceived differently regardless of the relative RLs. Argos LCs for the 18 locations included four LC2 (i.e., with estimated error of <500 m), 10 LC1s (i.e., with estimated error of <1.5 km), and four LC0s (i.e., with undefined error). Locations were obtained less than a minute from the

[3] While there was no overlap between sonar transmissions and tag data for the false killer whales tagged in June 2012, there is overlap between the two data sets for a false killer whale tagged in July 2013.

closest associated 53C MFAS transmissions for 14 of the 18 locations, with the remaining time intervals between locations and MFAS transmissions of 1.1, 2.55, 12.0, and 15.8 min. Distances between the tagged animal location and the ship using 53C sonar ranged from 11.1 to 63.8 km. Modeled maximum RLs in the upper 50 m of the water column at tagged animal locations ranged from 147 to 168 dB (Table 2), while minimum RLs in the upper 50 m ranged from 122 to 147 dB. Two of the four LC2 locations were at time intervals of <1 min and 1.1 min from corresponding 53C sonar pulses; modeled maximum RLs in the upper 50 m for these were 155 and 168 dB, respectively, while minimum RLs were 137 and 147 dB, respectively. Water depths, determined from geographic information system (GIS) analyses, at the 18 animal locations corresponding with the 53C sonar pulses, ranged from 12 to 491 m (median = 49 m), while the distances offshore ranged from 0.54 to 7.87 km (median = 2.51 km). Locations of the tagged individual on the 3 days of sonar use and 1 day prior to sonar use are shown in Figure 1. Time-series of sonar use, vessel-animal ranges, and modeled RLs are given in Figure 2. The tagged bottlenose dolphin remained in the same area off the western side of Kaua‘i both before the SCC and in the 3 days of the SCC (Figure 2).

Short-finned pilot whales

Three tagged short-finned pilot whales (two satellite-tagged in February 2011 and one satellite-tagged in February 2013) had both spatial and temporal overlap with MFAS transmissions (Table 1). The two individuals tagged in 2011 were tagged when MFAS was already in use in the area and, therefore, no information is available on their locations prior to MFAS transmissions. Analyses thus focused on the individual tagged in February 2013 (GmTag070). Twenty-four locations of GmTag070 were available for modeling RLs from the 53C sonar, and 22 of these were also modeled for RLs from the 56 sonar. An additional five locations were available for modeling RLs from the 56 sonar. In all five cases when modeled RLs were only available from the 56 sonar, estimated RLs at either 10-m depth or 200-m depth were <60 dB. When modeled RLs were available for both the 53C and 56 sonars, levels for the 53C sonar at 10-m depth ranged from 24 to 76 dB higher than those from the 56 sonar; thus only RLs from the 53C are considered in detail below. Argos LCs for the 24 locations associated with 53C sonar levels included four LC2, 11 LC1, 7 LC0, and 2 LCB (i.e., with undefined error). Locations were obtained less than a minute from the closest associated 53C MFAS pulse for 10 of the 24 locations, while the remaining time intervals between locations and MFAS transmissions ranged from 2 to 90 min. Distances between the tagged animal locations and the ship using 53C sonar ranged from 22.1 to 138.6 km. Modeled RLs from the 53C sonar at 10-m depth ranged from 90 to 162 dB for these periods (Table 2). Two of the four LC2 locations were within 1 min from sonar pulses; modeled RLs at 10-m depth associated with these locations were 126 and 155 dB. The short-finned pilot whale tag was a depth-transmitting satellite tag. Dive data obtained from this period indicated that dives immediately prior to and after the modeled RLs of 155 dB were to 575.5 and 687.5 m, respectively, indicating the tagged animal passed through the modeled depth ranges of both 10 m and 200 m. Bottom depth at the location, determined from GIS analysis, was 968 m, so dives were not to the bottom.

Modeled RLs at 200-m depth for all 24 locations ranged from 11 to 113 dB lower (median = 33 dB) than levels at 10-m depth. Water depths, determined from GIS analyses, at the 24 animal locations corresponding with the 53C sonar pulses ranged from 410 to 3,942 m (median = 1,622 m), while the distances offshore ranged from 5.66 to 33.19 km (median = 13.27 km). Locations of GmTag070 on the 3 days of sonar use and 1 day prior to

sonar use are shown in Figure 3. During the first day of MFAS use the tagged individual moved into an acoustic shadow south of the island of Niʻihau. During the last day of sonar use the animal moved in a fairly directional manner towards PMRF, with increasing RLs as it approached closer to the area of ongoing MFAS transmissions on the range (Figure 3). A time-series of sonar use periods, vessel-animal ranges, and modeled RLs are shown in Figure 4. All modeled RLs are shown, but it should be noted that for some of the quite low levels, masking from typical ambient noise would likely render these signals undetectable to the tagged animal.

During MFAS transmissions from 0800Z (Greenwich Mean Time) on 19 February 2013 through 0100Z on 22 February 2013, a 64.86-hr period, dive and surfacing data were available for 61.16 hr (94.3 percent of the total time). During this period, 190 dives (≥20 m) were recorded, a rate of 3.11 dives/hour. Mean dive depth during this period was 290.7 m (maximum = 1,011.5 m), while mean dive duration was 8.70 min (maximum = 19.43 min). We chose a similar time period prior to sonar exposure to compare diving behavior, from 0808Z on 16 February 2013 through 0101Z on 19 February 2013, a 64.87-hr period. During this period, dive and surfacing data were available for 54.30 hr (83.7 percent of the total). During this period, there were 268 dives, a rate of 4.93 dives/hour. Mean dive depth was to 157.2 m (maximum = 1,071.5 m), while mean dive duration was 6.44 min (maximum = 20.03 min). An example of combined location and dive data for an approximately 17-hr period during the highest levels of sonar exposure, as the animal approached closer to PMRF, is shown in Figure 5.

Rough-toothed dolphins

Location data were available for two individual rough-toothed dolphins (SbTag002, SbTag003) from a period that included overlapping MFAS data (Table 1). The two dolphins tagged were associated during this period (Baird et al. 2012); thus, results from the two individuals are not independent, and some details (i.e., depth, distance from shore) are presented only for SbTag002, which had 15 locations from which RLs from MFAS were estimated. Ranges of distance from MFAS to the tagged individuals and modeled maximum RLs are given in Table 2. Maximum RLs in the upper 20 m of the water column for both individuals were from LC1 locations (SbTag002, 144dB, SbTag003, 145 dB) using time intervals between the locations and MFAS sonar of <1 min and 4.05 min, respectively. Water depths, determined from GIS analyses, at the 14 locations of SbTag002 corresponding with the 53C sonar pulses ranged from 524 to 2,762 m (median = 871 m), while the distances offshore ranged from 9.45 to 21.45 km (median = 12.67 km). Maps showing locations of SbTag002 on four consecutive days are shown in Figure 6. A time-series of sonar use, vessel-animal ranges, and modeled RLs are shown in Figure 7.

DISCUSSION

These results demonstrate that this novel approach of pairing location and dive data from satellite-tagged individuals with modeled RLs from PAM data recorded on PMRF is a viable and promising method of estimating MFAS exposures for animals in realistic training scenarios. These tools provide a unique opportunity to examine potential individual reactions over longer periods of time and in terms of larger-scale movements over realistic geographical scales than is possible with other observational (e.g., only using PAM or aerial- or vessel-based observations) and experimental (e.g., short-term behavioral response studies with high-resolution acoustic tags) methods. However, in addition to the small sample size of tagged individuals available for

analyses, there were several factors that limited our ability to assess potential reactions to MFAS. The lack of available PAM data in association with the 2012 RIMPAC exercise, and for several days before and after each SCC, limited detailed comparisons both in the presence and absence of sonar. While MFAS use does occur within a set window for SCCs, MFAS use can also occur outside of those periods as well, although the extent of use is unknown. For example, the highest modeled RLs for the rough-toothed dolphin SbTag002 occurred shortly after the end of the SCC (Figures 5 and 6). Without a complete PAM record, it is not possible to definitively conclude that animals had not been exposed to MFAS in days prior to the scheduled SCCs. Subsequent tag deployments would thus benefit from additional PAM recordings for additional days immediately before and immediately after scheduled MFAS use. Recording of vessel positions, headings, and transmit times for MFAS during future training events would also benefit analyses, in particular as the vessel heading relative to the tagged animal (e.g., heading towards or away from the tagged animal) may be important context for interpreting potential reactions to MFAS exposure. Finally, the lack of control over MFAS sonar use limits the ability to relate any specific responses to particular aspects of exposure in a dose-response kind of analysis. Nevertheless, this analysis considers realistic MFAS transmissions in the context of actual training with baseline behavior and movements before, during and following MFAS. Even with the caveats noted above, these data and the development of this methodology represent significant progress in efforts to obtain direct measurements of potential responses of marine mammals to MFAS. They are directly informative to the assessment of potential behavioral responses using increasingly realistic exposure scenarios that are timely and relevant to the Navy in meeting its environmental compliance requirements.

The relatively few locations available for each tagged individual each day also limited the number of occasions when tag data corresponded closely in time to MFAS transmissions for estimating RLs. This is based in part on the duty cycling of the tags, but is also a fundamental limitation of using satellite tags in low-latitude areas. The Argos receivers are on polar orbiting satellites, which pass over the study area infrequently compared to higher-latitude areas, and often are low on the horizon, limiting the duration of the overpasses. Locations are only obtained with the serendipitous repeated surfacing of tagged animals during these short-duration overpasses. Duty cycling the tags, in terms of the number of hours per day they are set to transmit, reflects the tradeoff between the number of transmissions per day and battery life. Given the primary questions being addressed when the tags were originally deployed, the tags were programmed for a smaller number of hours per day than may have been optimal for maximizing the number of locations with short-time intervals before or after MFAS use during the SCCs. Depending on the timing of field operations relative to the start of SCCs, duty cycling of tags used in future monitoring could be modified to increase the number of hours per day tags will be transmitting. While this should increase the likelihood of obtaining a larger number of locations each day for calculating RLs, tagging in low latitude areas ultimately limits the number of locations that can be obtained.

Despite these limitations and acknowledging the small sample sizes of individuals tagged, the results obtained for each species are both unique and important to consider. The tagged bottlenose dolphin remained in the same area off the western side of Kaua‘i both before the SCC and in the 3 days of the SCC surface ship MFAS use (Figure 1), despite its proximity (11.1 to 63.8 km) to the vessels using MFAS, and maximum modeled RLs of 147 to 168 dB (Table 2). Based on photo-identification and genetics there appears to be a small population of

bottlenose dolphins resident to the islands of Kaua‘i and Ni‘ihau (Baird et al. 2009; Martien et al. 2011), and this population is recognized by the National Marine Fisheries Service as a discrete stock (Carretta et al. 2011). The individual TtTag010 had not been previously photo-identified off the island, and no other individuals in the group it was tagged in were photographed (Baird et al. 2013c). However, 3 days after it was first tagged, this individual appeared to repeatedly associate with another tagged bottlenose dolphin that was known to be part of the resident island-associated population (see Figure 6 in Baird et al. 2013a). In addition, in February 2014, subsequent to these analyses, this individual was photo-identified off Kaua‘i associated with individuals known to be part of the resident, island-associated population (Cascadia Research Collective, unpublished). Thus, TtTag010 can be considered to be part of the resident population. Given that MFAS has been used regularly on the PMRF range for over 30 years, it is likely that this individual has been repeatedly exposed to MFAS for a number of years, and given the lack of apparent large-scale movements out of the area, may have habituated to such exposures. It is also possible the prey availability in that area was much higher than in other areas of the animal’s range, thus the individual had particular motivation for saying in the area despite the relatively high RLs. This does not necessarily indicate that there were no subtle behavioral responses of this animal to individual MFAS transmissions or that these exposures may have had some other types of effects (e.g., physiological stress) during this period. However, the lack of large-scale movements despite the relatively high RLs over spatial scales of tens of km likely experienced by this animal is a notable observation relative to probabilistic functions of behavioral response and exposure dose being applied by the U.S. Navy and derived by various scientists that would predict a relatively high probability of significant behavioral reactions at these RLs (Finneran and Jenkins 2012).

Based on previous photo-identification and satellite-tagging efforts, there also appears to be a resident island-associated population of short-finned pilot whales that uses the Kaua‘i and Ni‘ihau area, although the range of individuals from this population is much greater than for the island-associated population of bottlenose dolphins, including some offshore waters and extending to off the western side of the island of O‘ahu (Baird et al. 2013a, 2013c). The individual short-finned pilot whale considered in our analyses had been previously photo-identified off the islands of Kaua‘i and O‘ahu (Baird et al. 2013a) and was also tagged off Kaua‘i previously in February 2011 (Baird et al. 2011b). Movements of the individual over a 37-day period in February and March 2011 were restricted to the area around Kaua‘i, Ni‘ihau, and western O‘ahu (see Figure 7 in Baird et al. 2011b; GmTag51). Given the wider-ranging movements of the island-associated population of short-finned pilot whales, they are likely exposed to MFAS on PMRF less frequently than the resident population of bottlenose dolphins, although adult and subadult individuals in this population have likely been exposed to audible levels of MFAS multiple times over their lives. In terms of interpreting the movements of the short-finned pilot whale in the context of exposure levels, over an approximately 13-hr period from 0756Z to 2121Z on 21 February 2013, the pilot whale moved from a distance of approximately 105 km from the destroyer that was using the 53C sonar, to approximately 22 km from the destroyer (Figure 3), with modeled RLs at 10-m depth increasing from an estimated 126 dB to 154 dB (Figure 4). While this animal was very likely exposed at levels that would be sufficient for detection of MFAS prior to this later period and thus may have generally habituated to the on-going event, the fact that it continued to approach PMRF and to tolerate increasing RLs of MFAS is also an important consideration for dose-exposure function for behavioral probability in odontocetes.

As noted for bottlenose dolphins and short-finned pilot whales, photo-identification evidence indicates that rough-toothed dolphins off the islands of Kaua‘i and Ni‘ihau show some fidelity to the area over multiple years (Baird et al. 2008, 2013c). Rough-toothed dolphins are found in deeper waters farther offshore than bottlenose dolphins in this area. While tagged rough-toothed dolphins have moved around Kaua‘i and Ni‘ihau, Kaulakahi Channel between the islands, located in the southern portion of PMRF, is a high-use area (Baird et al. 2013c). Maximum RLs in the upper 20 m of the water column around the tagged rough-toothed dolphins ranged between 113 and 144 dB (Table 2, Figure 7), with the highest RLs occurring after the end of the SCC. While the data from the rough-toothed dolphins are more limited than those for the bottlenose dolphin and the short-finned pilot whale, they are similar in failing to indicate broad-scale movement into areas where RLs would be lower.

In summary, these analyses integrating long-term tracking of individuals using satellite-tagging technology and U.S. Navy-standard propagation modeling with information about MFAS transmissions provide a useful demonstration of this novel approach and its potential applications and improvements. The ability to coordinate existing research methods with on-going analyses of marine mammal PAM during SCC training events was a significant step forward. This approach has limitations, as acknowledged above. However, the demonstrated ability to track individual movement and diving behavior for relatively long periods around MFAS training events offers the chance to assess individual behavior in periods with and without sonar. This is not possible with PAM-only monitoring of acoustic ranges, nor with short-term behavioral response study approaches. As demonstrated in other Navy ranges (Tyack et al. 2011), an integrated suite of methods utilizing different approaches (including the promising new methods demonstrated here) to address different aspects of these difficult questions is likely the best path forward. Given the inherent challenges in working offshore around PMRF, the use of satellite tagging methods integrated with PAM proves to be an increasingly important part of an integrated approach.

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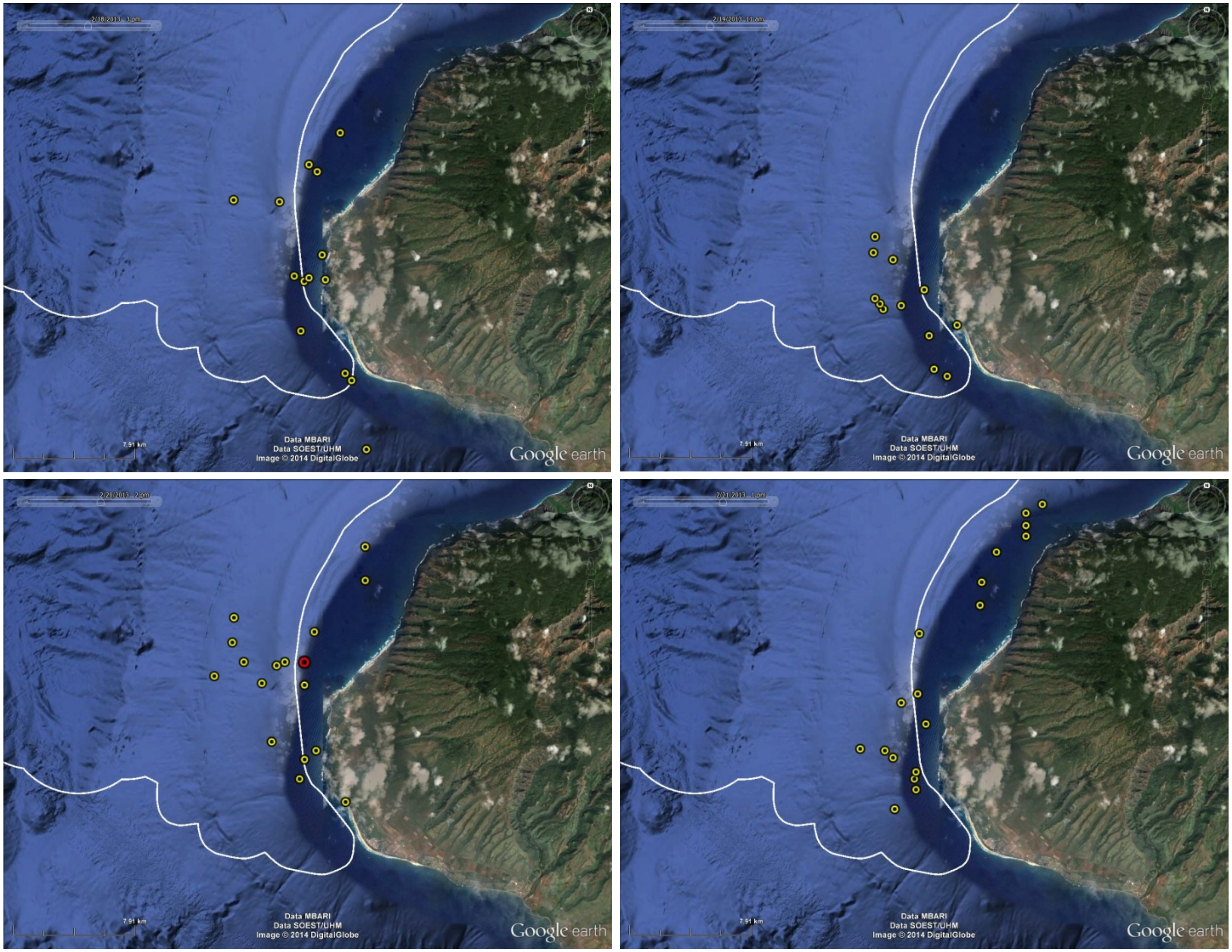

Figure 1. Locations of bottlenose dolphin TtTag010 over four 24-hour periods (all dates in GMT): 18 Feb 2013 (upper left); 19 Feb 2013 (upper right); 20 Feb 2013 (lower left); 21 Feb 2013 (lower right). The PMRF boundary is shown by the solid white line. There was no MFAS on PMRF on 18 Feb 2013. The location (on 20 Feb 2013, lower left panel) associated with the highest modeled RL (168 dB) is indicated by a larger red symbol.

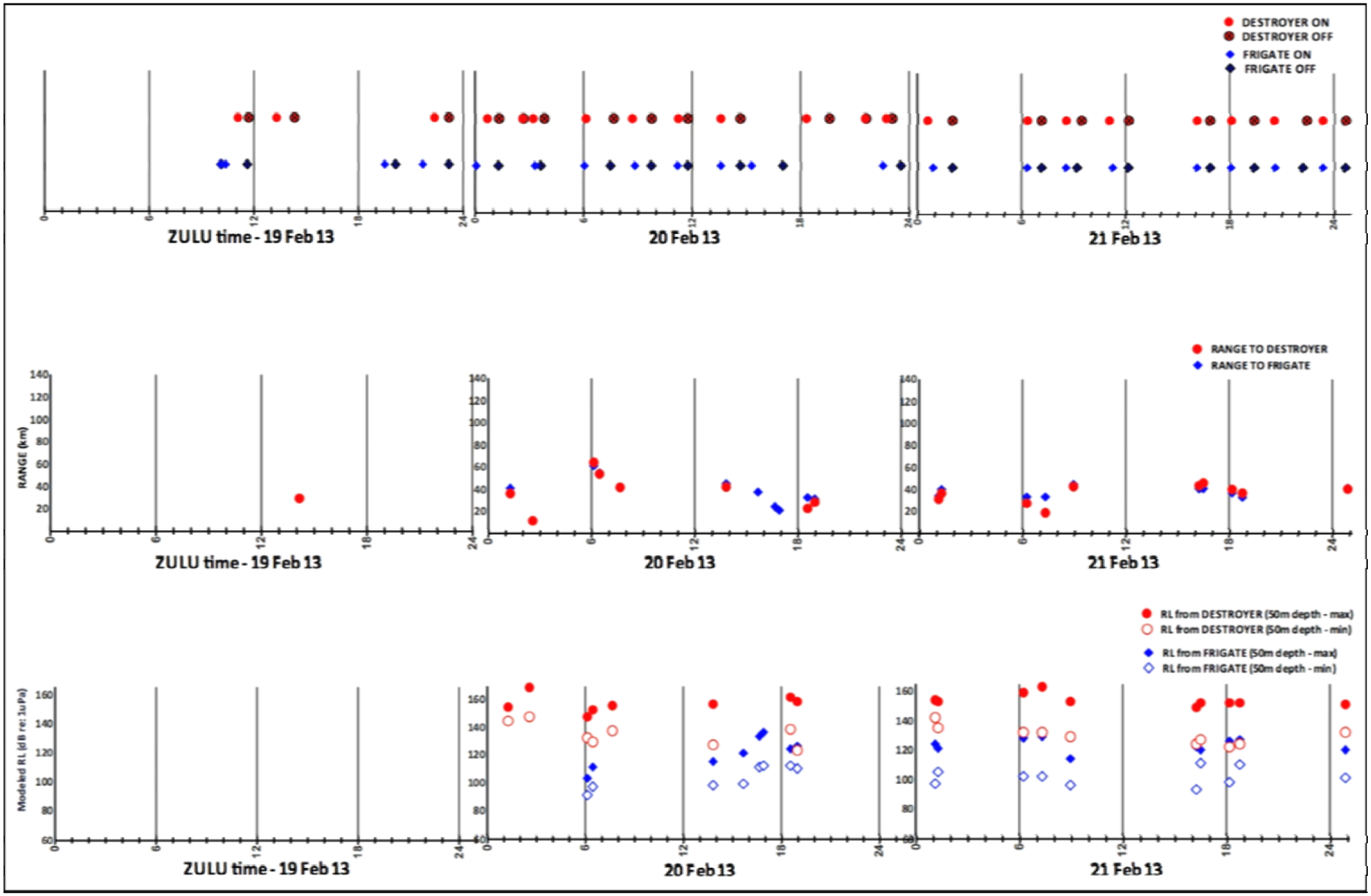

Figure 2. Timelines of sonar use (top), distance between tagged bottlenose dolphin (TtTag010) and vessels (middle), and modeled RLs (bottom). No RLs were calculated for 19 Feb 2013 due to long time intervals between MFAS pulses and locations from TtTag010.

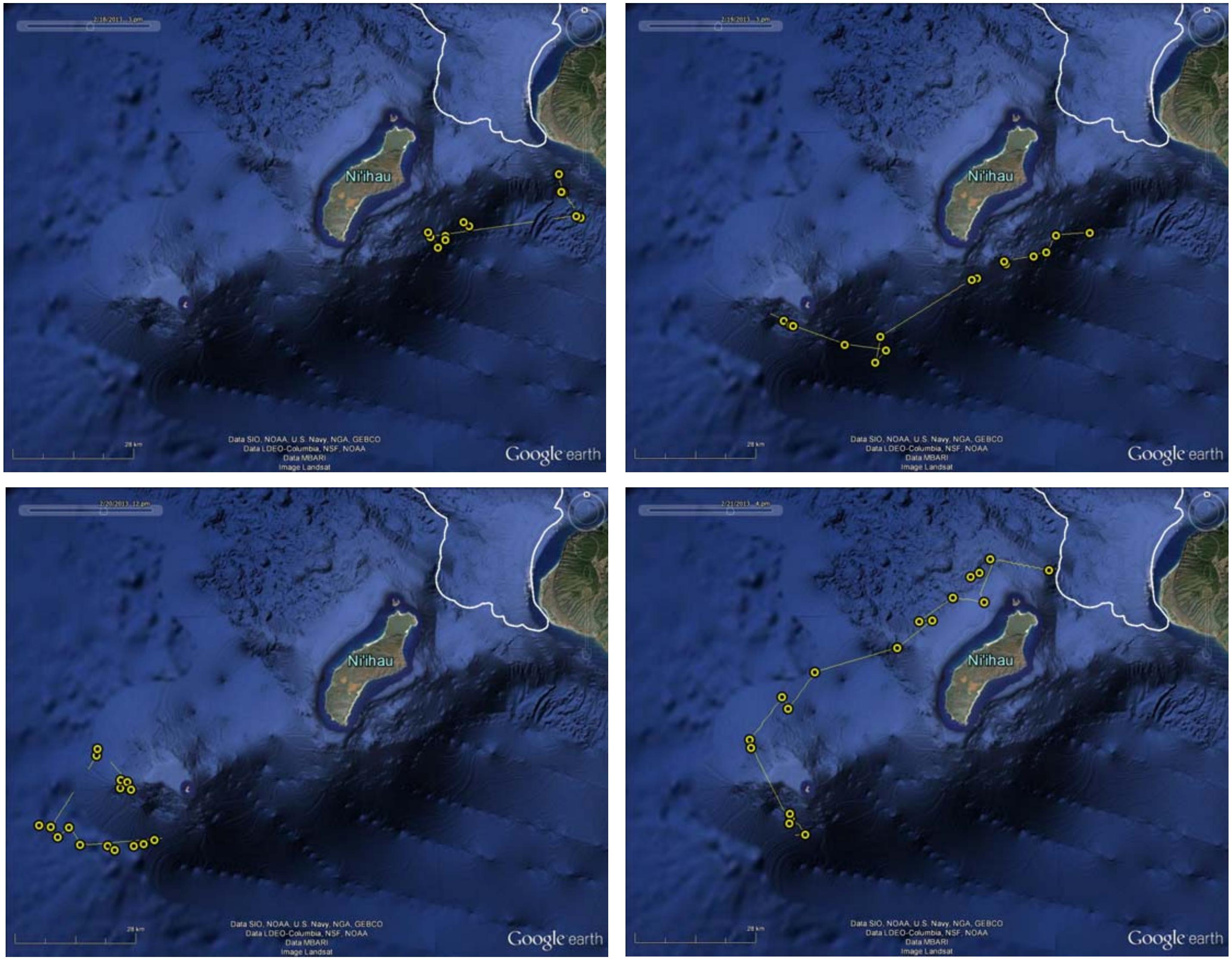

Figure 3. Locations of short-finned pilot whale GmTag070 over four approximately 24-hr periods (all dates shown in GMT): 18 Feb 2013 (upper left), 19 Feb 2013 (upper right), 20 Feb 2013 (lower left); 21 Feb 2013 through 0102Z on 22 Feb 2013 (lower right). The PMRF boundary is shown. There was no MFAS on PMRF on 18 February 2013. The yellow line represents periods when surfacing and dive data were available.

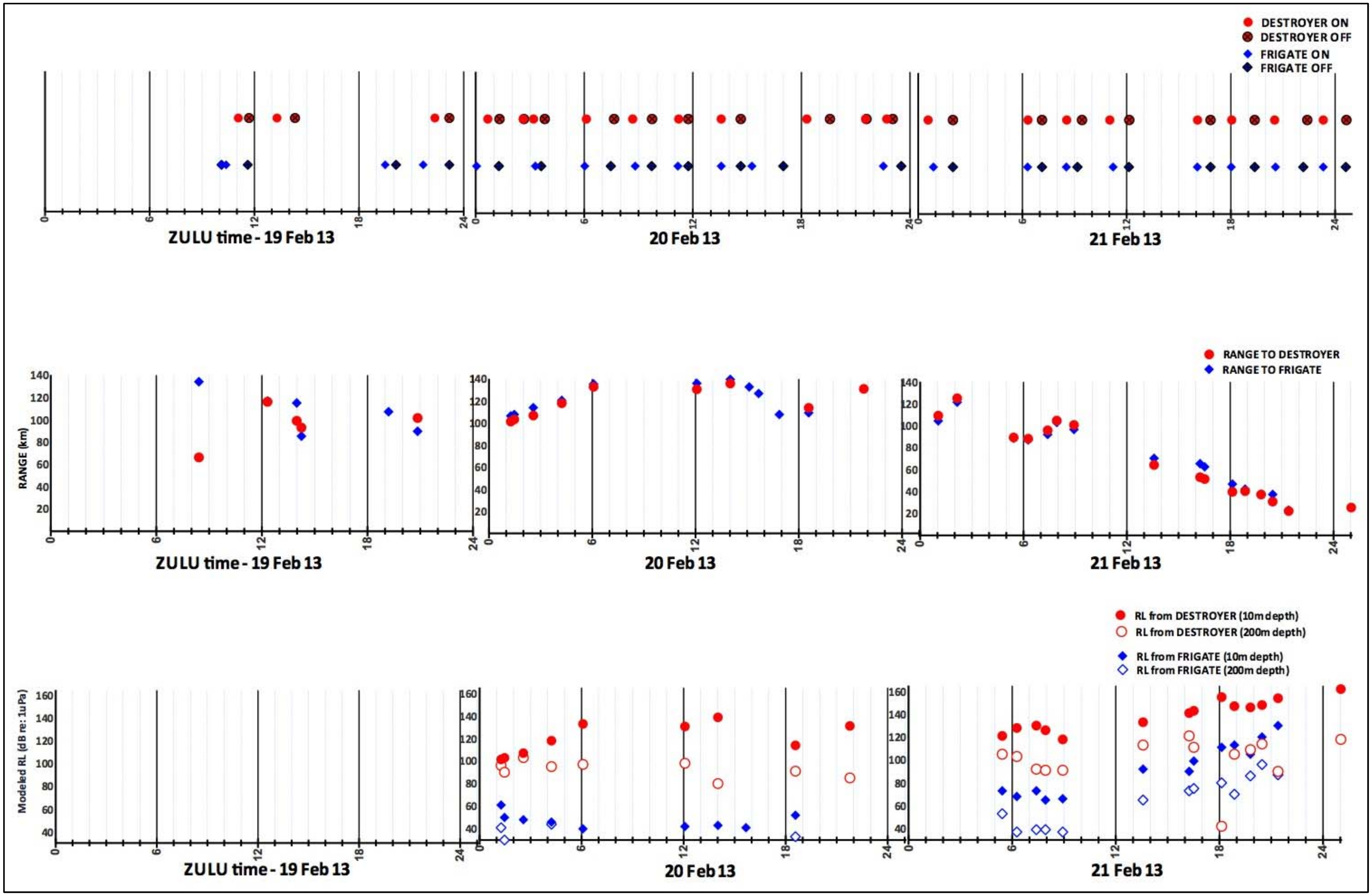

Figure 4. Timelines of sonar use (top), distance between tagged short-finned pilot whale (GmTag070) and vessels (middle), and modeled RLs (bottom).

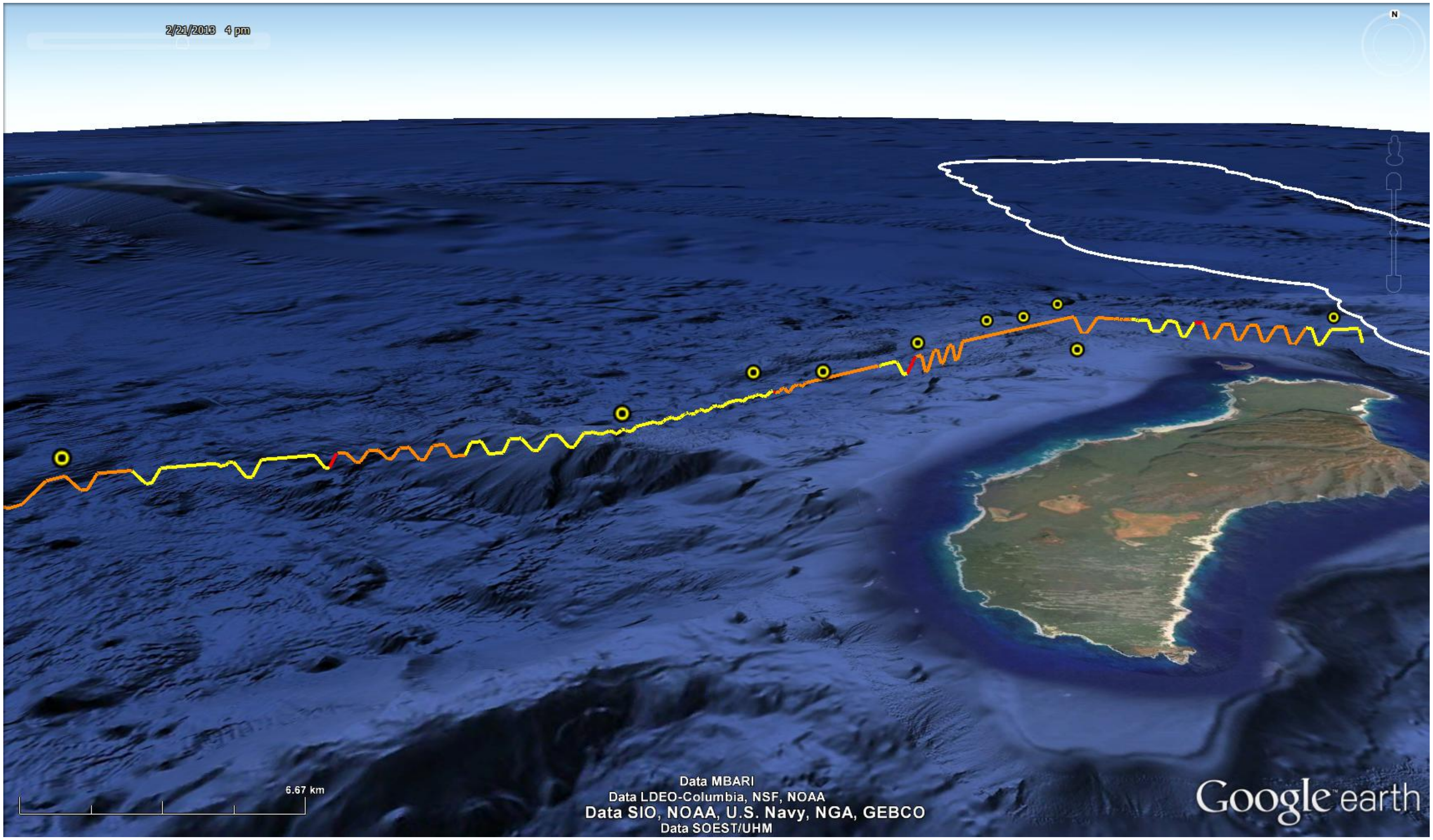

Figure 5. A pseudotrack of location and dive data from GmTag070 from 0848Z on 21 Feb 2013 through 0130Z on 22 Feb 2013, as the animal traveled from the southwest (left) to the northeast (right). The PMRF boundary is shown as a thick white line to the northeast of Ni‘ihau. Argos location estimates are shown as yellow circles, while dive data are represented by the continuous line, with color coding of yellow when no 53C sonar was occurring, red during the onset of 53C sonar and orange during continued periods of 53C sonar. Estimated RL at 0856Z on 21 Feb 2013 (far left, LCB, <1 min from sonar pulse) was 118 dB, while at 0102Z on 22 Feb 2013 (far right, LC0, 23 min after sonar pulse) was 162 dB. Dive depth during the deepest dive shown was to 1,011 m.

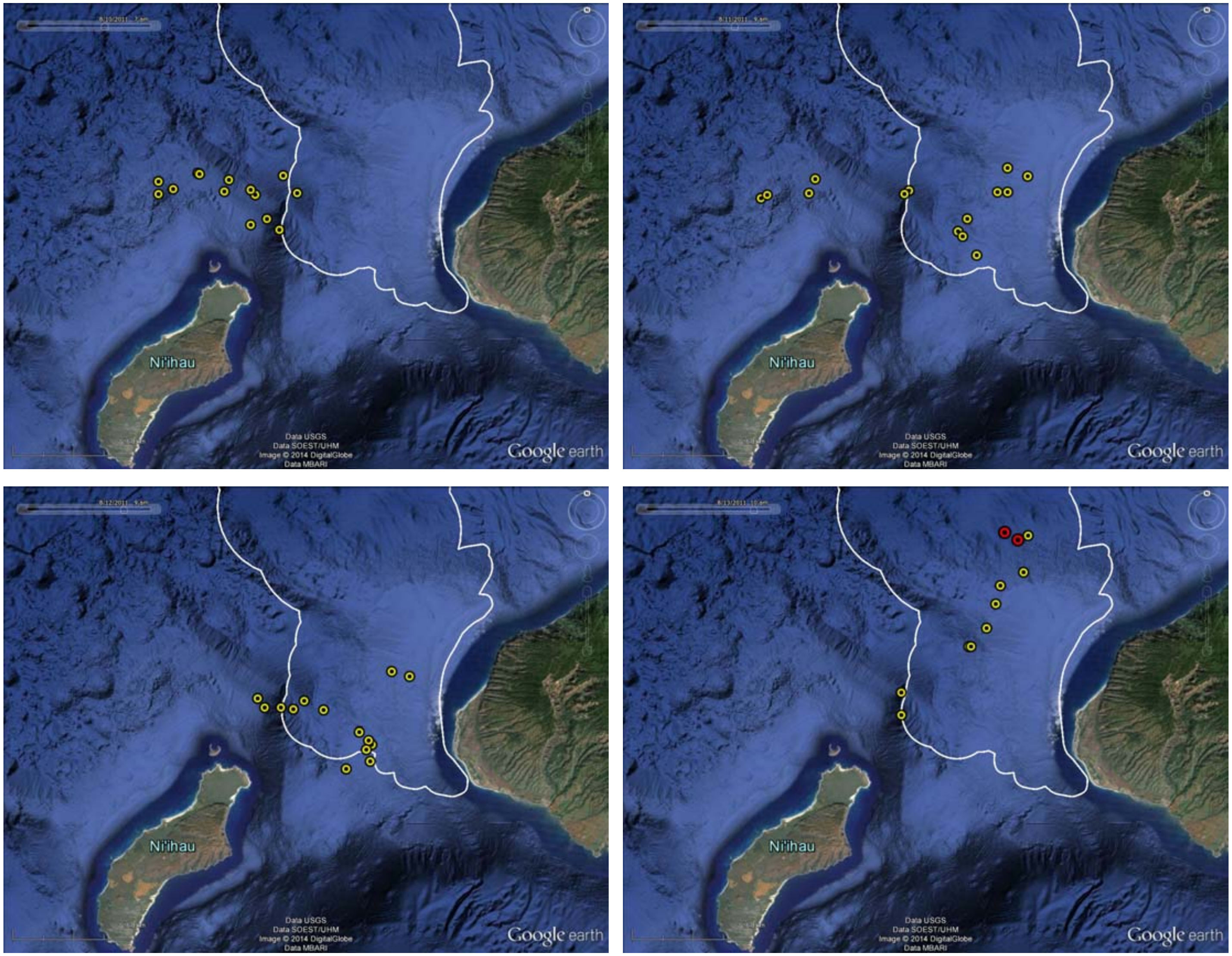

Figure 6. Locations of rough-toothed dolphin SbTag002 on four consecutive days (all days in GMT): 10 Aug 2011 (upper left); 11 Aug 2011 (upper right); 12 Aug 2011 (lower left); and 13 Aug 2011 (lower right). The PMRF boundary is shown. The two locations with highest RLs (144 dB) on 13 Aug 2011 are highlighted (larger red circles). These exposures were not part of the SCC.

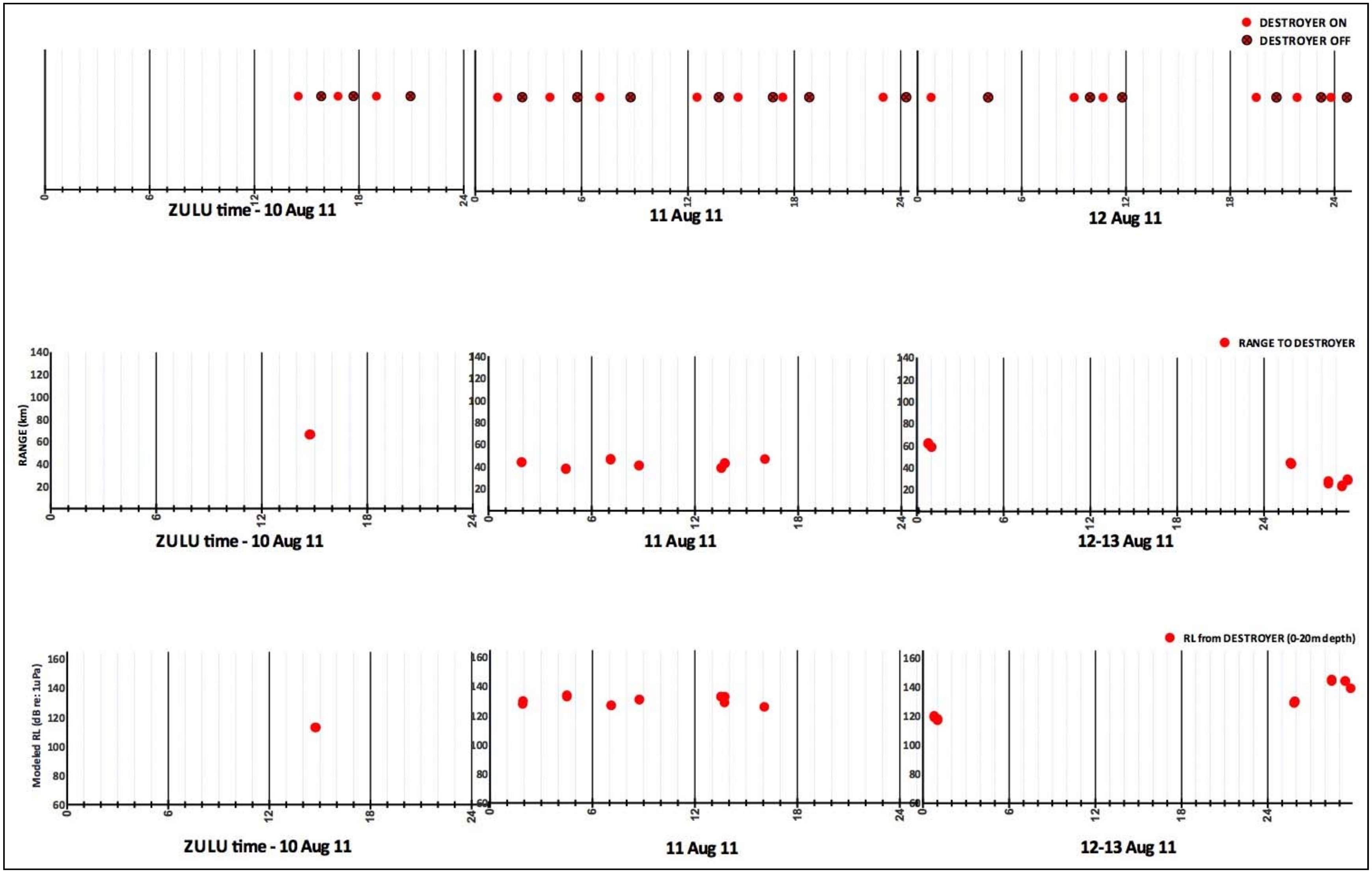

Figure 7. Timelines of MFAS use (top) during Aug 2011 SCC, distance between tagged rough-toothed dolphins (SbTag002 and SbTag003) and vessel (middle), and modeled RLs (bottom). The sonar used was a 53C. The highest estimated RLs between approximately 0400Z and 0600Z on 13 Aug 2011 were a destroyer using MFAS after the end of the SCC.

Table 1. Preliminary assessment of overlap between animal satellite-tag data and PMRF range acoustic recordings with and without MFAS transmissions between February 2011 and February 2013

Period	# consecutive days overlap between animal tag data and PAM archives			Species (#) with overlap between satellite tag data and MFAS transmissions	Species (#) with tag data with limited or no spatial and temporal overlap with MFAS
	Immediately before MFAS use	During MFAS use	Immediately after MFAS use		
Feb 2013	5	3	<1	*Gm* (1), *Tt* (2)	*Tt* (1), *Sb* (1)
Jun/Jul 2012	NA	NA	NA	0	*Pc* (3), *Sb* (3), *Tt* (2)
Jan/Feb 2012	NA	NA	NA	0	*Gm* (2), *Sb* (1)
Jul/Aug 2011	5	3	3	*Sb* (2), *Tt* (1)	*Sb* (1)
Feb 2011	NA	1	3	*Gm* (2)	*Gm* (1)

Key: # = number of; *Gm* = short-finned pilot whale (*Globicephala macrorhynchus*); MFAS = mid-frequency active sonar; NA = not applicable; *Pc* = *Pseudorca crassidens;* PMRF = Pacific Missile Range Facility; *Sb* = rough-toothed dolphin (*Steno bredanensis*); *Tt* = bottlenose dolphin (*Tursiops truncatus*).

Table 2. Summary of MFAS exposure modeling for satellite-tagged individuals

Individual	Tag type	# locations with range and modeled RLs	Range of distance to MFAS (km)	Range of modeled maximum RL from 53C dB re: 1µPa RMS	Range of modeled minimum RL from 53C dB re: 1µPa RMS	Maximum modeled RL dB re: 1µPa RMS (associated tag LC code) delta time (min)
SbTag002*	SPOT5	15	23.8 – 66.4	113 – 144	-	144 (LC1) <1.0
SbTag003*	SPOT5	14	22.8 – 66.2	113 – 145	-	145 (LC1) 4.05
TtTag010	SPOT5	18	11.1 – 63.8	147 – 168	122 – 147	168 (LC2) 1.1
GmTag070	Mk10-A	30	22.1 – 138.6	90 – 162	42 – 121	162 (LC0) 23

Key: *Individuals SbTag002 and SbTag003 were together during this period, so values are not independent; # = number of; 53C = AN/SQS-53C sonar; dB re: 1µPa = decibel referenced to a pressure of 1 micropascal; Gm = short-finned pilot whale (*Globicephala macrorhynchus*); km = kilometer(s); LC = location class; min = minute(s); RL = received level; RMS = root mean square; Sb = rough-toothed dolphin (*Steno bredanensis*); SPOT = Smart Position or Temperature Transmitting Tag; Tt = bottlenose dolphin (*Tursiops truncatus*).